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(54) **METHOD AND APPARATUS FOR LOCAL LOOP CLOSURE**

USPC ..... 415/1; 700/72, 37; 365/189.05  
See application file for complete search history.

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**G05B 19/042** (2006.01)  
**G05B 15/02** (2006.01)

(52) **U.S. Cl.**

CPC . **F02C 9/00** (2013.01); **G05B 15/02** (2013.01);  
**G05B 19/0426** (2013.01); **G05B 2219/23115** (2013.01)

(58) **Field of Classification Search**

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(56) **References Cited**

**U.S. PATENT DOCUMENTS**

4,719,891 A	1/1988	Porth et al.	
4,926,821 A *	5/1990	Porth et al.	123/399
4,984,505 A *	1/1991	Leeson et al.	91/361
6,202,012 B1 *	3/2001	Gile et al.	701/48
2003/0097511 A1 *	5/2003	Choi et al.	710/305
2010/0064657 A1	3/2010	Mahoney et al.	
2010/0127655 A1 *	5/2010	Ward et al.	318/621
2010/0223902 A1	9/2010	Mailander et al.	

**OTHER PUBLICATIONS**

EP Search Report for corresponding application No. 13157260.4-1807 dated Feb. 25, 2015.

Unofficial English Translation of Chinese Office Action issued in connection with corresponding CN Application No. 201310063876.6 on Aug. 28, 2015.

\* cited by examiner

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(57) **ABSTRACT**

A method and apparatus for local loop closure is provided. The apparatus includes a component for use in a gas turbine engine. The component includes at least one of an actuator and a servo-valve, at least one sensor, and an electronic module comprising controller electronics and memory. The electronic module is configured to receive and process commands for the at least one of an actuator and a servo-valve and queue received commands in an input buffer.

**6 Claims, 3 Drawing Sheets**

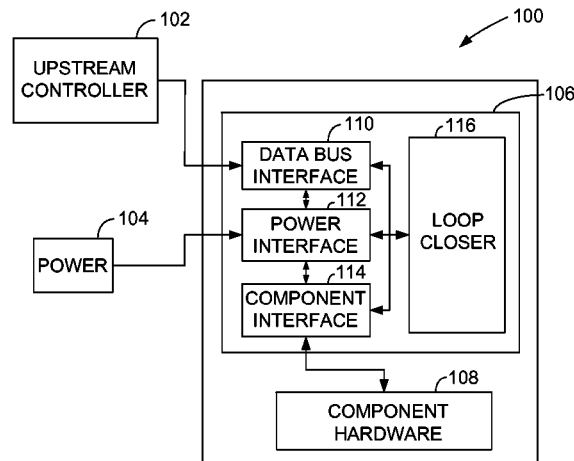


FIG. 1

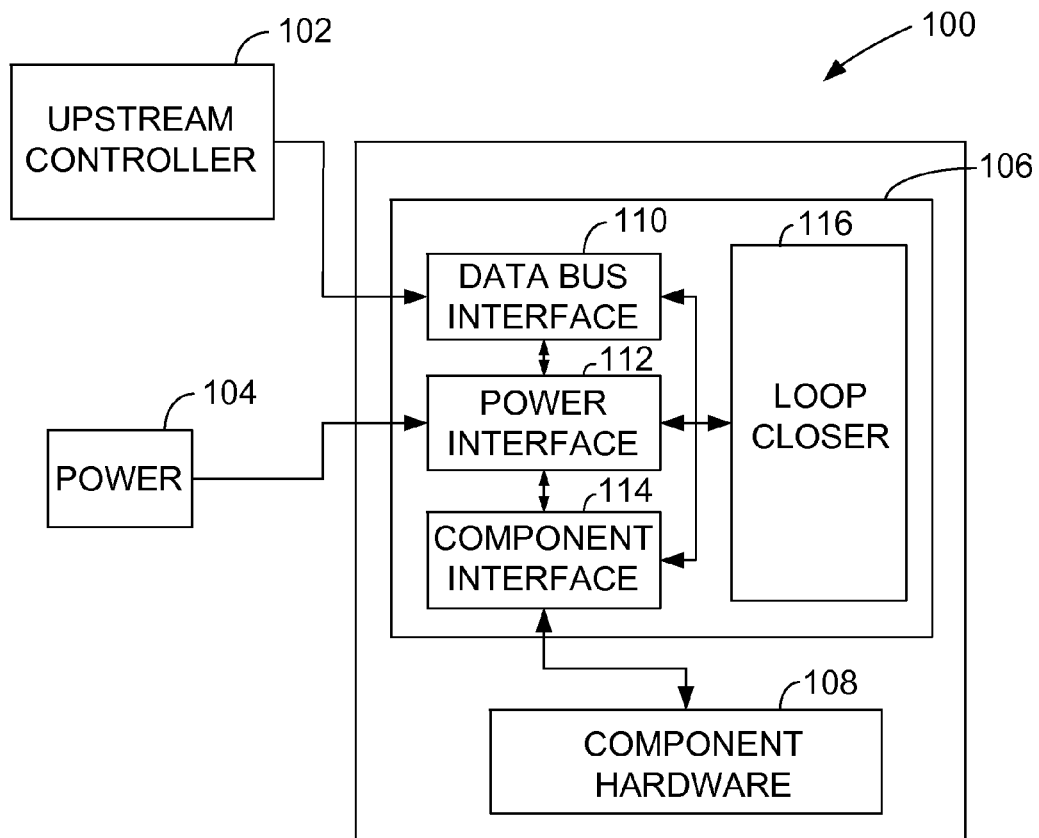


FIG. 2

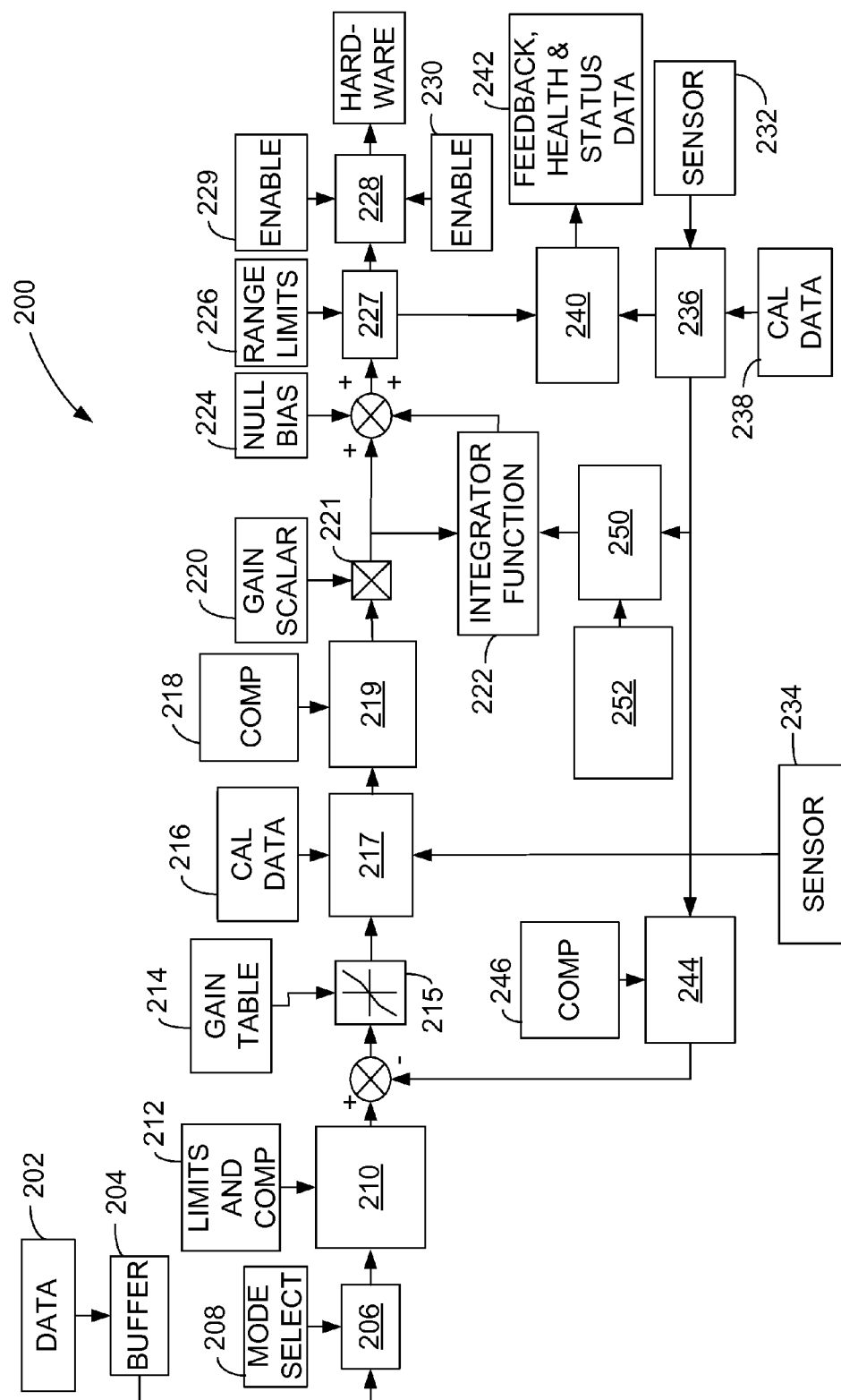
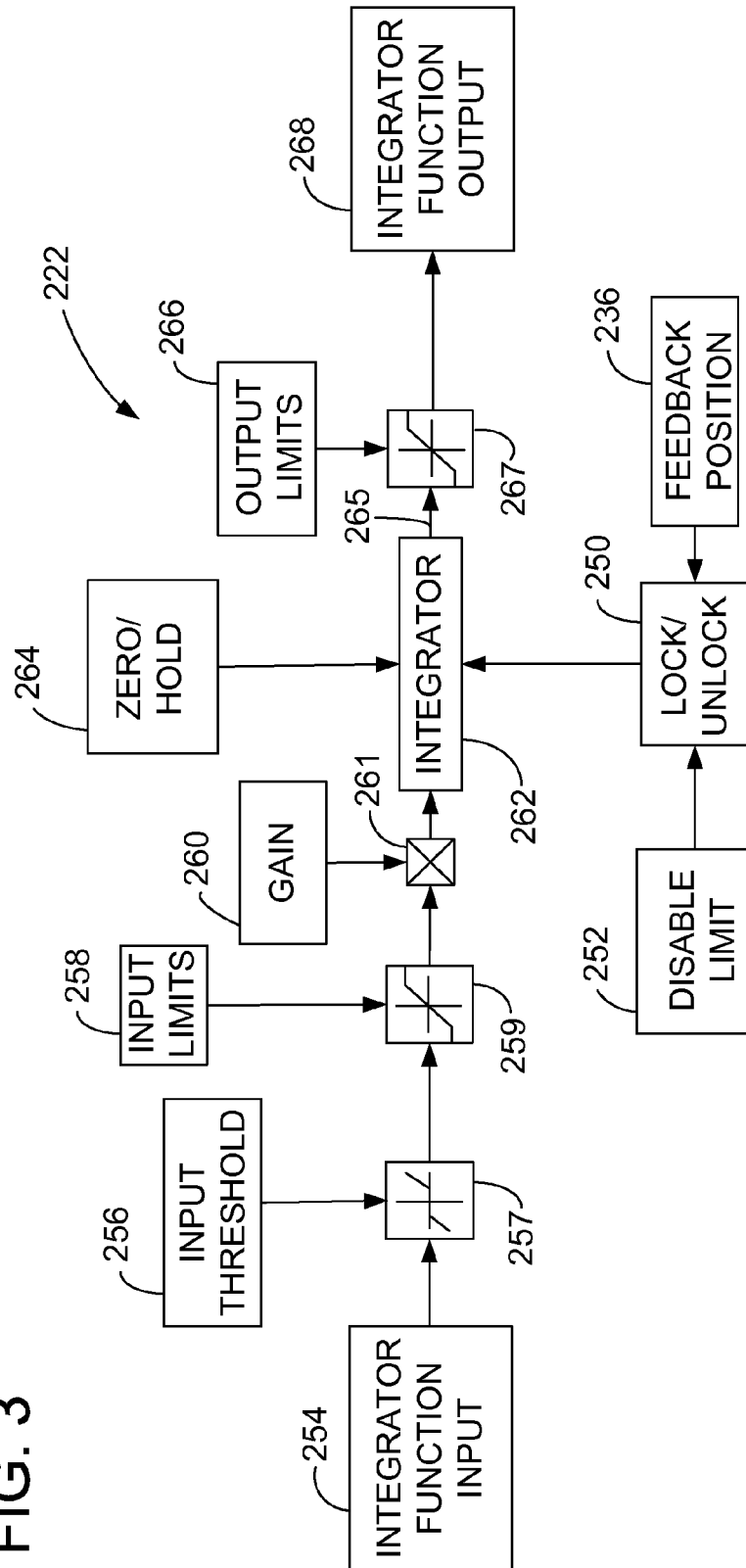


FIG. 3



## METHOD AND APPARATUS FOR LOCAL LOOP CLOSURE

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to Provisional Patent Application No. 61/605,067 filed Feb. 29, 2012, which is hereby incorporated by reference in its entirety.

### BACKGROUND

The field of the invention relates generally to local loop closure of a component for use in a gas turbine engine.

Generally, gas turbine engines have numerous variable geometry features which are typically actuated by closed loop hydro-mechanical control systems. These control systems are typically comprised of actuators, sensors, and servo-valves all driven by loop closing electronics and software. The loop closing electronics and software reside in an electronic engine control unit that is positioned a significant distance away from the actuation hardware resulting in substantial electrical cabling, as well as control delays due to the separation. The amount of electrical cabling between these components is known to drive a significant portion of the weight within an engine as well as offer additional opportunities for failures. When system failures occur, it is often difficult to tell which part has failed due to the separation. Often, as a result of the failures, unsuccessful maintenance is undertaken or a “shotgun maintenance” approach is used, wherein several parts are removed at once to insure the problem is resolved.

### BRIEF DESCRIPTION

In one embodiment, a component for use in a gas turbine engine is provided. The component includes at least one of an actuator and a servo-valve, at least one sensor, and an electronic module comprising controller electronics and memory. The electronic module is configured to receive and process commands for the at least one of an actuator and a servo-valve and queue received commands in an input buffer.

In another embodiment, a method for use in operating a component of a gas turbine engine is provided. The method includes receiving, by the component, commands for a hardware module of the component, processing, by the component, the received commands for the hardware module, and queuing, by the component, the received commands in an input buffer.

In yet another embodiment, one or more non-transitory computer-readable storage media having computer-executable instructions embodied thereon is provided. When executed by a processor, the computer-executable instructions cause the processor to receive, by a component of a gas turbine engine, commands for a hardware module of the component, process, by the component, the received commands for the hardware module, and queue, by the component, the received commands in an input buffer.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1-3 show exemplary embodiments of the method and system described herein.

FIG. 1 is a schematic view of a component in accordance with an exemplary embodiment of the present disclosure;

FIG. 2 is a data flow of the smart component shown in FIG. 1; and

FIG. 3 is a data flow of an integrator shown in FIG. 2.

## DETAILED DESCRIPTION

The following detailed description illustrates embodiments of the invention by way of example and not by way of limitation. It is contemplated that the invention has general application to analytical and methodical embodiments of sensing process parameters in industrial, commercial, and residential applications.

As used herein, an element or step recited in the singular and proceeded with the word “a” or “an” should be understood as not excluding plural elements or steps, unless such exclusion is explicitly recited. Furthermore, references to “one embodiment” of the present invention are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

FIG. 1 is a schematic view of a component 100 in accordance with an exemplary embodiment of the present disclosure. In the exemplary embodiment, component 100 is a hydro-mechanical control system that is used with a gas turbine engine. In the exemplary embodiment component 100 is driven by signals from upstream controller software 102 and power for component 100 is provided by power supply 104.

Component 100 includes an electronic module 106 that is in communication with component electrical hardware 108. In the exemplary embodiment, electrical hardware 108 includes, but is not limited to, linear or rotary actuators, position feedback sensors, and electro-hydraulic servo-valves. Electronic module 106 includes data bus interface circuitry 110, power interface circuitry 112, component specific circuitry 114, and a common loop closer module 116. Data bus interface circuitry 110 transmits signals from software 102 to component 100 and power interface circuitry 112 is in communication with power supply 104 that is configured to power component 100. Component specific circuitry 114 is in communication with component electrical hardware 108 and is configured to translate signals emanating from hardware 108 into module 106. In the exemplary embodiment, component specific circuitry 114 utilizes firmware and non-volatile media that is specific to hardware 108. In another embodiment the electronic elements 110, 112, 114, and 116 could be implemented as a single integrated design that provides similar functionality.

Common loop closer module 116 includes firmware, non-volatile media, and control electronics configured to process input signals and provide output demands to control hardware. In the exemplary embodiment, common loop closer module 116 is configured to receive communication from data bus interface circuitry 110, power interface circuitry 112, and component specific circuitry 114 and to process the communication locally within component 100.

FIG. 2 is a data flow 200 within component 100 shown in FIG. 1. In the exemplary embodiment, data 202 is introduced into flow 200 and received by a buffer 204. In the exemplary embodiment, data 202 are command signals utilized for operation of hardware 108. Alternatively, data 202 can be any signal that could be transmitted and processed by component 100 as described herein. In one embodiment, data 202 is received by buffer 204 every 10 milliseconds. Alternatively, data 202 can be updated to buffer at any time increment including but not limited to asynchronously, every 1 millisecond, every 2 milliseconds, and every 20 milliseconds. Data 202 can originate from any portion of a gas turbine including but not limited to software 102 shown in FIG. 1 or a primary processing unit such as a Full Authority Digital Engine Control (FADEC).

Buffer **204** is configured to queue data **202** before a mode is selected **206**. In the exemplary embodiment, when input signal **202** fails or command data signals **202** are not updated, the local controller can continue to close the loop, positioning hardware **108**, following the trajectory prescribed in buffer **204**, which was continuously updated with the desired failure position and trajectory information. In one embodiment, input buffer **204** includes failure instructions that command hardware **108** to operate in a predetermined manner as a result of a loss of input signal **202**.

In one embodiment, a mode is selected **206** from a mode select signal **208** that is not part of data **202**. Mode select **206** is a command relating to the operation of hardware **108**. Mode select **206** is configured to execute commands such as, but not limited to, an auto check, an auto calibration, a health test, and an inactivity command. After a mode is selected **206**, data **202** is subject to rate limiting and additional loop compensation **210**. In one embodiment, input limits **212** are provided that correspond to the specifics of component **100**. In the exemplary embodiment, the rate of data **202** is limited by the input limits **212** and modified by lead/lag dynamics to determine an optimal input signal for the loop.

A proportional gain table **214** is then utilized to provide **215** a shaped gain. Proportional gain table **214** supports both a simple fixed gain, or as an input adjustment, an increasing gain with error (gain kicker) for improved response tracking at high rates. In one embodiment, calibration data **216** is provided to hardware gain function **217** to modify data flow from gain **215**. In such an embodiment, calibration data **216** is retrieved from local non-volatile memory. Calibration data **216** includes information such as, but not limited to, trim, bias, gain, and potential dynamic compensation values which are used locally for signal calibrations and corrections. Calibration data **216** improves nominal feedback accuracy and hardware **108** null shifts and gains.

In the exemplary embodiment, loop compensation variables **218** are provided to loop compensation **219** to optimize closed loop dynamic response. In one embodiment, loop compensation variables **218** are phase leads that are updated by adjustment over the command data bus. A gain scalar **220** is applied to multiplier **221** to adjust for predictable gain variations. In the exemplary embodiment, gain scalar **220** is defined by adjustment over the command data bus. In another embodiment, gain scalar **220** is a function stored in local non-volatile memory. In the exemplary embodiment, an integrator function **222**, described in more detail below, is used to reduce tracking errors due to unpredicted servovalve null shifts and motion.

In the exemplary embodiment, a null bias **224** is provided to accommodate a predictable shift that may result from load or pressure changes. In one embodiment, null bias **224** is defined by adjustment over the command bus. In one embodiment, null bias **224** is normalized in units of actuator rate (e.g. %/sec). Null bias **224** is set for each specific application and assists a null bias integrator, and reduces transient impulse due to resets and channel transfers. In one embodiment, null bias **224** is used in real time to correct tracking errors due to pressure and load leakage.

Range limits **226** are then utilized by a torque motor driver **227** before being passed to a driver enable function **228** that is configured to allow control of hardware **108**. In the exemplary embodiment, range limits **226** support either active-active or active-standby architecture. In one embodiment, if two channels are being utilized for component **100**, half of range limits **226** would be used on each channel. Driver enable signal **229** is defined by adjustment over the command bus to disable driver **228** outputs. Driver enable **230** is an independent hard-

wired input signal that provides additional failure accommodation options, not available using only the data bus for channel selection. In one embodiment, driver enable **230** is jumpered in the component interface connector for applications where this function is not required.

In the exemplary embodiment, component **100** and flow **200** include sensors **232** and **234** that are configured to provide feedback to component **100**. Sensors **232** and **234** monitor engine operation and input real-time actual sensor data. Position feedback sensor **232** is used to close the position control loop, other sensors **234**, include pressures and temperatures within component **100**, but also may include other sensors across the engine, such as a fan inlet temperature sensor, a compressor inlet total pressure sensor, a fan discharge static pressure sensor, a compressor discharge static pressure sensor, an exhaust duct static pressure sensor, an exhaust liner static pressure sensor, a flame detector, an exhaust gas temperature sensor, a compressor discharge temperature sensor, a compressor inlet temperature sensor, a fan speed sensor, and a core speed sensor. Local sensors **232** and **234** facilitate operation of component **100** as well as local compensation for typical sources of variation such as temperature, pressure, and load.

In one embodiment, sensor **232** is a position sensor and sensor **234** is a pressure sensor that both provide feedback to a position calibration function **236**. Position calibration **236**, in addition to information received from sensors **232** and **234**, receives calibration data **238** from local non-volatile media. In one embodiment, data received by position calibration function **236** is coupled with data from torque motor driver **227** and transmitted to a health and status logic **240**, which outputs feedback, health and status data **242**. Feedback, health and status data **242** can include any information about component **100** including, but not limited to, position, voltages, currents and null bias information. In one embodiment, health and status data is utilized by the FADEC for higher level redundancy management & channel selection.

In one embodiment, data received by position calibration function **236** is transmitted to loop compensation **244** such that lead/lag dynamics can be optimized. In the exemplary embodiment, loop compensation **244** utilizes loop compensation variables **246** to modify feedback dynamic response characteristics before data is coupled with data emanating from rate limiting and loop compensation **210**. In one embodiment, loop compensations **210**, **219**, and **244** are operated such that if local inner loop operates at a significantly higher update rate and bandwidth on the command bus than biased position commands coming over the command bus from an upstream location, loop compensations **210**, **219**, and **244** can be utilized as a smoothing function to reduce inner loop noise caused by command stair-steps.

FIG. 3 is a data flow of integrator function **222** shown in FIG. 2. In the exemplary embodiment, data received by position calibration function **236** is transmitted to integrator function **222** via an integrator lock and unlock feature **250**. In one embodiment, hardware position based limits **252** are provided to feature **250** along with data received by position calibration **236** before being passed to integrator **262**. Feedback based integrator lock and unlock limits **252** are defined by adjustment over the command bus. In one embodiment, feature **250** is utilized as a separate feature, such that integration should reset to zero during power-up or reset.

In the exemplary embodiment, an integrator function input **254** is provided to integrator function **222** and modified **257** in relation to a threshold **256** to determine if integration is necessary. In one embodiment, threshold **256** is a discrete value, such as, but not limited to 1 milliamp. Alternatively, threshold

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256 can be any value that facilitates integration as described herein. Input 254 is then checked 259 against input limit 258 to limit the maximum integrator input before an integrator gain 260 is applied 261. In the exemplary embodiment integrator gain is defined by adjustment over the command bus and is a function of pressure or expected loads.

In the exemplary embodiment, an integrator 262 receives data from integrator lock and unlock feature 250, input 254, and zero/hold inputs 264. Integrator 262 then integrates to provide an integrator output 265. Output 265 is compared 267 with output authority limits 266 to determine if a present value of an error is determined to exceed a predetermined threshold. If a present value of an error is determined to exceed a predetermined threshold, an integrator function output 268 is limited to the output authority limit values 266. In the exemplary embodiment authority limits 266 are defined by adjustment over the command bus.

In the exemplary embodiment, integrator function 222 is shown to be placed after a gain scalar 220 is applied 221. However, integrator function 222 can be utilized anywhere within data flow 200 that facilitates local loop closing as described herein.

As used herein, the terms “software” and “firmware” are interchangeable, and include any digital signal flow logic stored in memory for execution by controller circuitry, including RAM memory, ROM memory, EPROM memory, EEPROM memory, and non-volatile RAM (NVRAM) memory. As used herein, the terms “controller” and/or “controller circuitry” include a processor configured to at least execute instructions and process signals. The above memory types are exemplary only, and are thus not limiting as to the types of memory usable for storage of logic and controller instructions.

As will be appreciated based on the foregoing specification, the above-described embodiments of the disclosure may be implemented using computer programming or engineering techniques including computer software, firmware, hardware or any combination or subset thereof. Any such resulting program, having computer-readable code means, may be embodied or provided within one or more computer-readable media, thereby making a computer program product, i.e., an article of manufacture, according to the discussed embodiments of the disclosure. The computer readable media may be, for example, but is not limited to, a fixed (hard) drive, diskette, optical disk, magnetic tape, semiconductor memory such as read-only memory (ROM), and/or any transmitting/receiving medium such as the Internet or other communication network or link. The article of manufacture containing the computer code may be made and/or used by executing the code directly from one medium, by copying the code from one medium to another medium, or by transmitting the code over a network. In the exemplary embodiment, all software logic located locally is firmware and does not change for most applications. The tuning/configuring of this firmware is provided by inputs from the upstream processors.

The above-described embodiments of a method and system for local loop closer provides a reliable means for closing electronics into a single unit. As such, processing demands on high demand processing systems is reduced. The elimination of cabling also provides a weight reduction to engines utilizing the methods and system described herein. Additionally, processing bandwidth can be increased significantly resulting in significant performance improvements. Also, improved reversionary modes and fault accommodation are provided with less hardware redundancy. Failure accommodation and reversionary modes are significantly improved over legacy, using the input buffer feature.

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The embodiments described above also provide smoothing & asynchronous operation features to support significantly higher loop closure update rates (<2 ms), enabling enhanced tracking performance and disturbance rejection, trajectory based input signal buffering for improved failure accommodation, and selectable maintenance modes and NVM storage of data to support automatic rigging and calibration. Additionally, fewer connections provide improved reliability, and improved supportability is provided due to better fault/failure isolation. Also because of the localization of processing, the embodiments above provide for improved reversionary modes and accommodation of failures. In the exemplary embodiment several input parameters are provided over the command data bus. These inputs are provided at various update rates, with the most time-critical command signals provided at the highest rate. Other less time-critical inputs, such as, but not limited to, compensation and limits can be provided at much lower rates to reduce data bus traffic without limiting loop closer performance. In another embodiment, many of these inputs do not require regular adjustment, and utilize data values stored as non-volatile memory within component 100. If adjustment is desired, these data values are replaced by data provided over the command data bus.

A technical effect of the systems and methods described herein includes at least one of: (a) receiving, by the component, commands for a hardware module of the component; (b) processing, by the component, the received commands for the hardware module; and (c) queuing, by the component, the received commands in an input buffer.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

The invention claimed is:

1. A method for use in operating a component of a gas turbine engine, the component comprising an electronic module comprising a controller and memory, and a control loop, said method comprising:

receiving, by the component, commands for a hardware module of the component;

processing, by the component, the received commands for the hardware module;

queuing, by the component, the received commands in an input buffer; and wherein the method further comprises providing a null bias integration to the control loop; and wherein said electronic module is further configured to receive and process a first input at a first data rate and a second input at a second data rate.

2. A method in accordance with claim 1, wherein the method further comprises storing failure commands within the input buffer.

3. A method in accordance with claim 2, wherein the method further comprises executing failure commands upon the loss of received commands in the input buffer.

4. A method in accordance with claim 1, wherein the method further comprises providing lead/lag compensation to the received commands.

5. A method in accordance with claim 1, wherein the method further comprises providing adjustable gains to the control loop.

6. A method in accordance with claim 1, wherein the method further comprises executing a health and status check of the component from instructions stored in local non-volatile memory. 5

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